0.1 Introduction

Climate risk assessment is becoming central in contemporary activities related in any way to the environment and whose assets could be affected by climate change. In particular, climate change risk assessment is a topic more and more organizations are considering in their decisions.

A climate change risk assessment for a given system is the analysis of the impacts of and the responses to climate change regarding that system. Various guidelines are available for these kind of risk assessments (cf. [?, ?, ?]) and slight variations of them are adopted by authors, but they do not specify precisely the practical details of the assessment. In particular, there is no objective method to choose the climate indicators used in the assessment, but they are selected according to their effectiveness in scientific literature and in previous assessments, combined with the personal experience of the authors. The choice of the indicators is far from objective.

0.1.1 Climate risk

But what is risk? Before introducing the methodology adopted to evaluate risk in the present work, first it is convenient to introduce a proper terminology. In this work definitions by International Organization for Standardization (ISO) are used for their concision. When some terms are not available, they are taken from Intergovernmental Panel on Climate Change (IPCC). Both sources have similar definitions for the same terms.

Risk is a general term which can be tailored to different contexts and applications as a measure of uncertain consequences on a system of interest.[1] A system is very broadly any concrete or abstract entity which can be affected by risk.

Example

Some possible systems which can be exposed to risks are any physical system, communities of people, an idea.

A paradigmatic example is the financial sector, where the concept of risk is widely known and is connected directly to economic value and the concept of portfolio, to the point that financial risk management can be considered a research field itself.[?] Examples on how other fields implement the concept are elaborated in [?, 14] and in [?].

In this work the risk related to climate change is: "effect of uncertainty", from [?].[2] IPCC proposes a similar definition, expanding on the entities

[1] Without delving into Philosophy, a source of change is needed to have consequences and it is specified by the definitions in use.

[2] Note that this definition is not specific to climate risk since no reference to climate is made.

involved (e.g. the possible systems) and the contexts in which the term is used, but focusing only on negative effects: "effect of uncertainty", from [?]. An important aspect of climate risk is that it originates both from impact of climate change, i.e. "effect on natural and human systems (3.3)", from [?], and any response to it, i.e. action enact to mitigate the effects of climate change or adapt to it. It is not common to see responses integrated into risk assessment, as exposed by [?, 492], and for the purposes of the present study they are neglected. Henceforth, terms climate risk and risk are used interchangeably.

To make the assessment easily extensible and modular, risk is defined as the result of the interaction of three elements, i.e. its determinants, namely hazard, exposure and vulnerability. Response is considered the fourth determinant of risk, when the adopted methodology includes it in the assessment. Definitions of determinants were introduced in [?, 69-70] and offer a change of direction from previous methodologies centered on the concept of vulnerability of the system instead of the overall risk (cf. [?] and [?]).

The hazard is defined by ISO as "potential source of harm", from [?] and is elaborated further by IPCC. In the following the term hazard is used to address to climate-related hazards without further specification. In [?, 2224] IPCC provides the term climatic impact-driver (CID) to address to climate-related physical phenomena with neutral effects (cf. [?, 10] or [?, 1871]). In other words, among the CIDs which can affect the system, only some may be regarded as hazards, depending on the risk assessed. Hazards used in the present work are selected among the taxonomy provided by European Union for climate change risk assessment (CCRA), to have a well-known and authoritative reference in the field.[?, 177]

The exposure of a system is determined by "presence of people, livelihoods, species or ecosystems, environmental functions, services, resources, infrastructure, or economic, social or cultural assets in places and settings that could be affected", from [?].

The vulnerability of a system is "propensity or predisposition to be adversely affected", from [?]. Properties of the system which determine its vulnerability may be classified further in sensitivity, i.e. "degree to which a system (3.3) or species is affected, either adversely or beneficially, by climate (3.4) variability or change", from [?], and adaptive capacity, i.e. "ability of systems (3.3), institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences", from [?]. This classification in general helps the analysis of the system and the identification of responses, e.g. adaptation measures may increase the adaptive capacity of some elements of the system.

Each determinant may be viewed as a collection of elements, which are of different nature depending on the determinant they belong to, but are addressed generically as drivers.[3] Physical elements of the system may be effectively considered as Drivers of this determinant.

Example

A tropical storm is a driver within the hazard determinant,[?, 15] income is a driver within the vulnerability determinant,[?, 493] airport structures (e.g. runways, aprons, terminals) in an airport (i.e. the system) are drivers within the exposure determinant.[?, 551] More examples are available in the references.

The concept of driver of risk is borrowed from [?] to allow a smooth extension to methodologies where risk is the result of complex interactions within and across determinants.

For a quantitative CCRA, numerical values must be associated to drivers. These values are called indicators and defined by ISO as: “quantitative, qualitative or binary variable that can be measured or described, in response to a defined criterion”, from [?].[4] There can be more than one way to describe numerically the same driver, hence the choice is not unique and the resulting risk may be affected by it. In the following, the term indicator written alone refers to an indicator of a driver within the hazard determinant, to relax the lenghty wording. For the other determinants the full qualification is used.

Having introduced the definitions above, the various components of risk can be arranged as in figure 1. It sum up the relation between the various components, highlightning the fact that risk depends on drivers from three independent categories and are quantified possibly in multiple ways.

0.1.2 Methodology

Restricting the treatise to climate-related applications is not sufficient to fix details on risk, e.g. how to evaluate it from its determinants. These implementation details depend on which methodology is chosen to perform the risk assessment, which is presented in this section and is defined operatively in section ??.

The methodology of CCRA applied in the present work follows [?] and its upgrade [?] to the concepts presented in section 0.1.1. The latter should be read in parallel with the former and superseds the outdated concepts.

This methodology is split in eight modules, each dependent on the previous ones. The following is an overview of them:

[3]When this terminology has not been applied, it is common to refer to drivers with the name of the determinants they belong to, e.g. drivers within the vulnerability determinant are simply called vulnerabilities.

[4]The definition by IPCC is not as general because focuses only on the climate system and there is no specific term for the same concept applied to the other determinants.

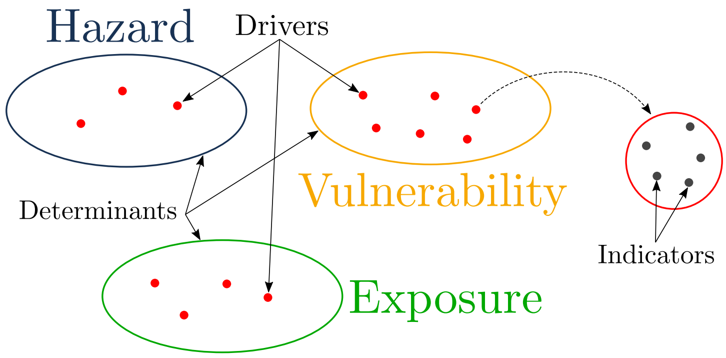


Figure 1: A possibile representation of the components of climate risk. Climate hazards can affect exposed and vulnerable elements of the system and determine a risk for it. Collectively these factors are called drivers and can grouped in the three independent determinants of risk: hazard, exposure and vulnerability. To provide quantitative results, each driver is described by numerical values, i.e. the indicators, each providing a different possible description or measure of the same driver.

1. understand the context in which the assessment is framed and identify objectives, scope and resources involved;[**?**, 39-53]

2. identify risks and impacts affecting the system under study and determine drivers of hazard, exposure and sensitivity;[**?**, 26-41]

3. choose indicators for each driver of hazard, exposure and sensitivity;[**?**, 73-84]

4. collect data and quantify indicators;[**?**, 87-103]

5. normalise indicators to allow their comparison;[**?**, 105-119]

6. for each determinant, weight normalised indicators and aggregate them into a single value;[**?**, 121-131]

7. aggregate values for individual determinants into a single value for risk;[**?**, 133-141]

8. present the results of the CCRA.[**?**, 143-154]

Even if a complete application of this methodology does not fall within the purposes of the present study, each module is briefly addressed in section **??** when case studies are treated.

0.1.3 Structure of the document

The landview of terms and definitions used in climate change risk assessment is varied and this may cause confusion. For the sake of clarity, definitions are provided, along with the sources they are taken from. If no specification of the source is present, the definition is assumed to be taken from [?] or [?]. Terms which are present in both sources have equivalent definitions.

Definitions of terms used in the document are collected in the Glossary and are reachable by hyperlinks directly from the text in the digital version of the document.

0.2 Data

Climate data show great complexity in structure and availability (e.g. essential climate variables (ECVs) can be represented as multidimensional objects, some climate datasets are collections of ECVs). For these and other properties discussed in [?], climate data can be regarded as big data.

In this work a generic ECV V can be represented mathematically as a scalar function

$$V : S_{\text{lat}} \times S_{\text{lon}} \times S_{\text{time}} \to \mathbb{R} \tag{1}$$

where S_{lat}, S_{lon} and S_{time} are domains of latitude, longitude and time dimensions, respectively.[5] Every numerical value is equipped with proper units of measurement, to represent physical quantities correctly. As a consequence, the codomain in equation (1) is partially wrong: with an abuse of notation, it represents only the magnitude of the ECV and does not consider the unit of measurement. This is a small exception to simplify the notation and in the remainder of this document units of measurement are always addressed explicitly.

A more practical representation of V is a multidimensional array, where values in the domain are coordinates associated to each dimension and each entry of the array is the result of V evaluated on those coordinates. Figure 2 shows this representation visually. In the following, this representation is used to simplify the discussion and same ECV name is used both for the function and the multidimensional array.

Example

Near-Surface Air Temperature, symbol tas, is available for some coordinates and timestamps. It can be seen as the scalar function in equation (1), which associates each value in set $S_{\text{lat}} \times S_{\text{lon}} \times S_{\text{time}}$ to a value with unit K, or it can be represented as the multidimensional array in figure 2, where each entry is function (1) evaluated at the corresponding coordinates.

[5] In contexts related to Machine Learning these objects are called tensors. Since they may not satisfy the mathematical definition of a tensor, in particular the map may not be multilinear and the numerical sets may not be vector spaces, no reference to such objects is made in this work.

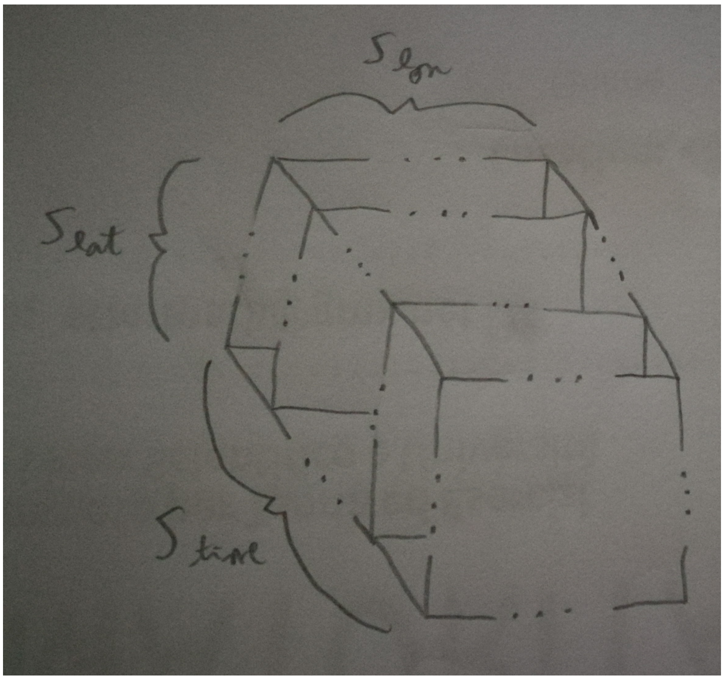


Figure 2: Representation of a generic ECV as multidimensional array.

Normals used as reference depends only on spatial coordinates, hence they are functions

$$\bar{V} : S_{\text{lat}} \times S_{\text{lon}} \to \mathbb{R} \tag{2}$$

or equivalently, multidimensional arrays with spatial coordinates only. Normals are evaluated as explained in [**?**, 6] using an averaging period specific to each case study (cf. section **??**).

Indicators of drivers within the hazard determinant are functions of ECVs and additional parameters. In general they are aggregated over the temporal dimension and in this work their evaluation is performed for each year, i.e. the indicator has yearly resolution or is evaluated with yearly frequency. In this work an indicator I can be defined mathematically as

$$I : S_{\text{lat}} \times S_{\text{lon}} \times S_{\text{y}} \times \prod_{p \in P_I} S_p \to \mathbb{R} \tag{3}$$

where S_{y} is a set of the years considered during the analysis, P_I is the set of parameters for that indicator and S_p is the set of values available for each parameter $p \in P_I$.[6] An indicator can be represented as a multidimensional array, similarly to ECVs. The dependence of an indicator on ECVs is not clear in the definition given by equation (3), but in the following this is made explicit by the context or by the definition of the indicator.

[6] As a symbolic shortcut, if $P_I = \emptyset$ then the indicator is defined only over $S_{\text{lat}} \times S_{\text{lon}} \times S_{\text{y}}$.

Example

The indicator $\mathrm{TX_x}$ is evaluated for the period 1991-2020 with yearly frequency. This indicator is the monthly maximum value of daily maximum temperature,[**?**] hence:

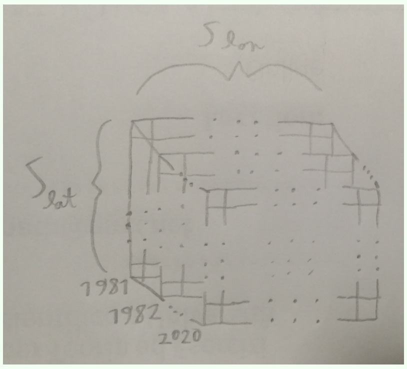
- it depends on ECV tasmax defined at daily frequency over the considered period,

$$S_{\text{time}} = \left\{ t : \begin{array}{l} t \text{ day from 1st January 1991} \\ \text{to 31st December 2020} \end{array} \right\} \quad ;$$

- spatial dimensions are not specified, hence the evaluation is performed for each point of an arbitrary set $S_{\text{lat}} \times S_{\text{lon}}$;
- no additional parameters are required, $P_{\mathrm{TX_x}} = \emptyset$;
- the outcome is a scalar value for each year in the period,

$$S_{\text{y}} = \{1991, 1992, \ldots, 2020\} \quad ;$$

- the multidimensional array representation of the indicator is in the following figure, where each entry is a real value in K:



Indicators of drivers within exposure and vulnerability determinants may be defined similarly as the hazard determinant as scalar functions depending on specific variables characterising the system.

Definitions

adaptation “process of adjustment to actual or expected climate (3.4) and its effects”, from [?]. 2

adaptive capacity “ability of systems (3.3), institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences”, from [?]. 2

climatological standard normal “averages of climatological data computed for the following consecutive periods of 30 years: 1 January 1981-31 December 2010, 1 January 1991-31 December 2020, and so forth”, from [?, 2].. *see* average

determinant Any component of risk, i.e. hazard, exposure, vulnerability, response, from [?, 493].. 2, 3, 4, 6, 7

driver individual components of determinants, from [?, 493]. *see* determinant, hazard, vulnerability, exposure & response, 3, 4, 6, 7

exposure “presence of people, livelihoods, species or ecosystems, environmental functions, services, resources, infrastructure, or economic, social or cultural assets in places and settings that could be affected”, from [?]. 2, 3, 4, 7

hazard “potential source of harm”, from [?]. 2, 3, 4, 6, 7

impact “effect on natural and human systems (3.3)”, from [?]. 2, 4

indicator “quantitative, qualitative or binary variable that can be measured or described, in response to a defined criterion”, from [?]. 3, 4, 6, 7

normal “period averages computed for a uniform and relatively long period comprising at least three consecutive ten-year periods”, from [?, 2].. *see* period average, 6

period average "averages of climatological data computed for any period of at least ten years starting on 1 January of a year ending with the digit 1", from [**?**, 2].. *see* average

response action enact to mitigate the effects of climate change or adapt to it. 2

risk "effect of uncertainty", from [**?**]. 1, 2, 3, 4

sensitivity "degree to which a system (3.3) or species is affected, either adversely or beneficially, by climate (3.4) variability or change", from [**?**]. 2, 4

vulnerability "propensity or predisposition to be adversely affected", from [**?**]. *see* sensitivity & adaptive capacity, 2, 3, 7

Acronyms

CCRA climate change risk assessment. 2, 3, 4

CID climatic impact-driver. 2

ECV essential climate variable. 5, 6, 7

IPCC Intergovernmental Panel on Climate Change. 1, 2, 3

ISO International Organization for Standardization. 1, 2, 3